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MATERIALS FOR ADVANCED TURBINE ENGINES (MATE) - PROJECT 4
EROSION RESISTANT COMPRESSOR AIRFOIL COATINGS
FINAL REPORT

By

M. Freling

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Project Manager, Susan M. Benford - Materials Division, NASA, Lewis Research Center, Cleveland, Ohio 44135

16. ABSTRACT
The performance of candidate erosion resistant compressor airfoil coatings installed in ground tested experimental JT8D and JT9D engines and subjected to cyclic endurance at idle, takeoff and intermediate power conditions has been evaluated. Engine tests were terminated prior to the scheduled 1000 cycles of endurance test due to high cycle fatigue fracture of the Gator-Gard plasma sprayed 88WC-12Co coating on titanium alloy airfoils. Coated steel (AMS5616) and nickel base alloy (Incoloy 901) performed well in both engine tests. Post test airfoil analyses consisted of binocular, scanning electron microscope and metallographic examinations.

17. KEY WORDS (SUGGESTED BY AUTHOR(S) Erosion, Coatings, Compressor Blades, Plasma Spray, Diffusion, Steel Alloys, Titanium Alloys, Nickel Alloys, High Cycle Fatigue, Binocular, Scanning Electron Microscope, Metallographic	18. DISTRIBUTION STATEMENT

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1.0 SUMMARY

The purpose of this program was to identify candidate compressor airfoil coatings and demonstrate the ability of these coatings to provide at least a 2X improvement in particulate erosion resistance. The compressor airfoil materials selected for this program were steel (AMS 5616), nickel (Incoloy 901) and titanium (AMS 4928) alloys. The objective of Tasks I through VI were to (1) identify coatings, (2) optimize the coating application process on specimens, (3) determine the procedures for coating compressor airfoils and (4) recommend coated airfoils for Task VII, engine testing. The results of Task VII are reported in this document.

The three compressor blade alloys selected for evaluation were coated with either of two plasma coating compositions by two plasma coating systems and by pack applied diffusion coatings. More specifically, the steel compressor airfoils were coated with 60 KW plasma sprayed 83WC-17Co, nickel airfoils were coated with Gator-Gard® plasma sprayed 88WC-12Co and pack diffusion applied Cr+B, and titanium airfoils were coated with Gator-Gard plasma sprayed 88WC-12Co. All of these coatings and blade alloys were tested in JT8D and JT9D ground based experimental engines. The tests were terminated due to high cycle fatigue fracture of the Gator-Gard plasma sprayed 88WC-12Co coating on titanium alloy airfoils. Coated steel or nickel alloy airfoils performed well in these engine tests.

2.0 INTRODUCTION

Background

Considerable gas turbine engine service experience has shown that ingestion of particulate debris is the major cause of compressor airfoil erosion. In the high compressor, this erosion has resulted in a change in airfoil shape which reduces engine performance. Under NASA contract NAS3-20632, Engine Component Improvement Program - JT9D Engine Diagnostics, a comprehensive study of the JT9D commercial aircraft engine fleet indicated that erosion and associated performance deterioration of the compressor were more sensitive to the number of engine cycles rather than engine operating hours. Erosion was observed to increase in severity for short routes where flight cycles rather than flight hours were the controlling factor. As a result of this fleet-wide problem, operating costs/hour of flight time have increased for airline operators.

Prior to the initiation of the subject contract, laboratory and rig testing at the Materials Engineering and Research Laboratory of Pratt & Whitney had indicated an improvement in erosion resistance for electro-deposited, plasma and pack applied compressor coatings. An especially good performing coating showing a 10X improvement in erosion resistance was titanium diboride on steel. However, when coated steel compressor blades were tested in a JT8D engine service evaluation program,the electro-deposited titanium diboride coating suffered from leading edge chipping which limited its usefulness. The leading edge chipping was also observed in laboratory tests. Rig testing indicated that the use of plasma applied coatings on airfoils could provide a reduction in erosion from two to four times as compared to current bill-of-material uncoated airfoils. Plasma applied tungsten carbide-cobalt coatings, to a thickness of 25.4 microns (1 mil), demonstrated reduced erosion behavior on both titanium and steel compressor airfoils. Furthermore, rig testing of plasma spray coated compressor blades indicated that these coating systems did not undergo the leading edge damage that has prevented the use of titanium diboride coatings. In addition to plasma coatings, diffusion coatings on nickel alloy compressor blades could be applied economically since there is a strong manufacturing base for these materials. In addition, previous limited testing had indicated diffusion coatings were capable of providing improved erosion resistance. As a result of this background, plasma and diffusion coatings were selected to be the primary low cost production, state-of-the art coating approaches evaluated to reduce erosion induced compressor performance deterioration.

To accelerate the development of material technologies, such as erosion resistant compressor airfoil coatings, to the point where they could be verified through engine testing, a cooperative Government/Industry effort, Materials in Advanced Turbine Engines (MATE), was initiated under NASA sponsorship.

This volume presents the FEDD category 2 technical effort accomplished in MATE Project 4. Category 2 data includes an engine test program and post test analysis of erosion coated compressor airfoils. Catagory 1 data was reported in Volume I (NASA CR 179622).

Approach

Plasma applied coatings have been evaluated quite extensively while limited experience has been obtained with diffusion coatings, particularly on steel and nickel alloys. To properly evaluate the material, processing, design and operating characteristics of erosion resistant coatings, a seven task approach was used for the selection, process definition, laboratory evaluation, design evaluation, coating optimization and fabrication and finally the engine test of candidate coatings.

The goal of this approach was to demonstrate coatings capable of improving the erosion resistance of steel (AMS 5616), nickel (Incoloy 901) and titanium (AMS 4928) alloy compressor airfoils by at least a factor of two. To meet the objectives of the program, the following tasks were performed.

- Task I - Coating Systems Selection - Available erosion resistant coating systems were reviewed to select plasma and diffusion coatings for use on steel (AMS 5616), nickel (Incoloy 901) and titanium (AMS 4928) alloys.

- Task II - Coating Comparison and Process Parameter Definition - Plasma (composition and/or process variables) and diffusion coating parameters were investigated to define the limits for applying the coatings selected in Task I to laboratory specimens. These parameters were evaluated by microstructural and visual characterizations.

- Task III - Laboratory Evaluation of Coatings - Plasma and diffusion coatings applied to steel, nickel and titanium alloys were more closely evaluated for erosion resistance, microstructure and composition. Coating/alloy combinations, along with uncoated baseline specimens were high cycle fatigue tested.

- Task IV - Design Analysis and Component/Coating Systems Selection - Steel, nickel and titanium alloy compressor blade designs were selected to demonstrate the effectiveness of the erosion resistant coatings. The effect of the coating on the fatigue strength of the blade was considered. Detailed analyses were conducted to locate the coating in the area of maximum erosion and to avoid coating sections of airfoils sensitive to fatigue.

- Task V - Airfoil Coating Optimization - Coating process parameters, masking and post-coating heat treatment, were optimized for application of the recommended coatings. Post-coat finishing techniques were developed to produce a 20-30 AA airfoil surface finish.

- Task VI - Component Fabrication and Test - Based on the processes developed in Task V, compressor blade designs for each alloy were coated for component testing. Rig erosion and component high cycle fatigue tests were performed and based on the results, one coating per alloy was selected for further evaluation.

- Task VII - Engine Testing - JT8D and JT9D ground based engine tests were performed to evaluate coated steel and titanium alloy airfoils and to evaluate coated nickel and titanium alloy airfoils, respectively. Both engines were scheduled to perform a 150-hour cyclic endurance test.

3.0 COMPONENT PROCESSING AND DEMONSTRATION ENGINE TEST PROGRAM

As a result of the Task VI effort, Component Fabrication and Test, the coatings recommended for engine test and the compressor alloy materials airfoil quantities were defined:

Engine Model	Stage	Airfoil Alloy	Quantity	Coating
JT8D	8	AMS 4928	30	Gator-Gard plasma spray 88WC-12Co
JT8D	12	AMS 5616	40	60 KW plasma spray 83WC-17Co
JT9D	7	AMS 4928	51	Gator-Gard plasma spray 88WC-12Co
JT9D	14	Incoloy 901	34	Gator-Gard plasma spray 88WC-12Co
JT9D	14	Incoloy 901	34	Pack Diffusion Cr+B

The coatings were applied by the following vendors:

Coating	Vendor
Gator-Gard 88WC-12Co	United Technologies Metal Products, Inc.
60 KW 83WC-17Co	General Plasma Associates, Inc.
Pack Diffusion Cr+B	Pratt & Whitney

(United Technologies Metal Products, Inc. is presently owned and operated by Sermatech, Inc.)

The plasma spray coatings were only applied to the outer 50% of the airfoil for all alloys. However, the pack diffusion Cr+B coating was applied to the entire Incoloy 901 airfoil. Surface finishing, using a Harperize mass polishing system, was performed on Incoloy 901 and AMS 4928 coated blades to achieve a surface smoothness of 20-30AA. On the AMS 5616 airfoils, the plasma spray coating which was applied to the outer 50% of the airfoil was overcoated with Sermetel 5380 to achieve the required 20-30AA surface finish (Figures 1 through 5). The Sermetal 5380 coating also provided corrosion protection for the lower 50% of the airfoil and blade attachment regions.

The coated airfoils were tested in ground based JT8D and JT9D experimental engines, which were designated as X-634-9 and X-579-32, respectively. Engine test programs comprised idle, takeoff and intermediate power conditions (Figures 6 and 7). While both engines were scheduled to be tested for 1000 cycles, the JT8D engine ran for 744 cycles while the JT9D accumulated 189 cycles prior to shutdown. Both engine test programs were typical of engine tests performed to evaluate component endurance.

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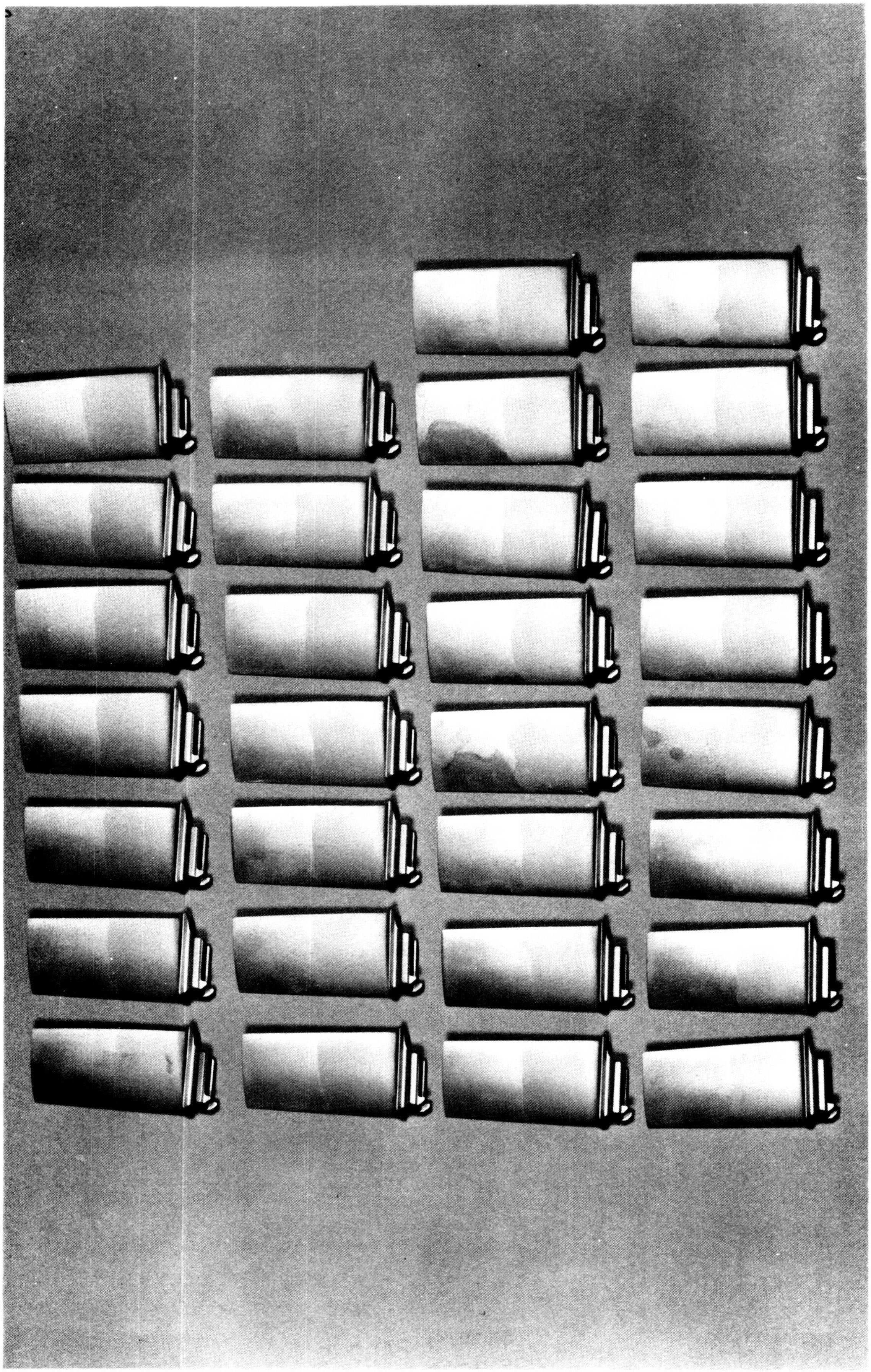

Figure 1 JT8D AMS 4928 8th Stage Compressor Airfoils Gator-Gard PLasma Spray Coated with 88WC-12Co and Media Finished

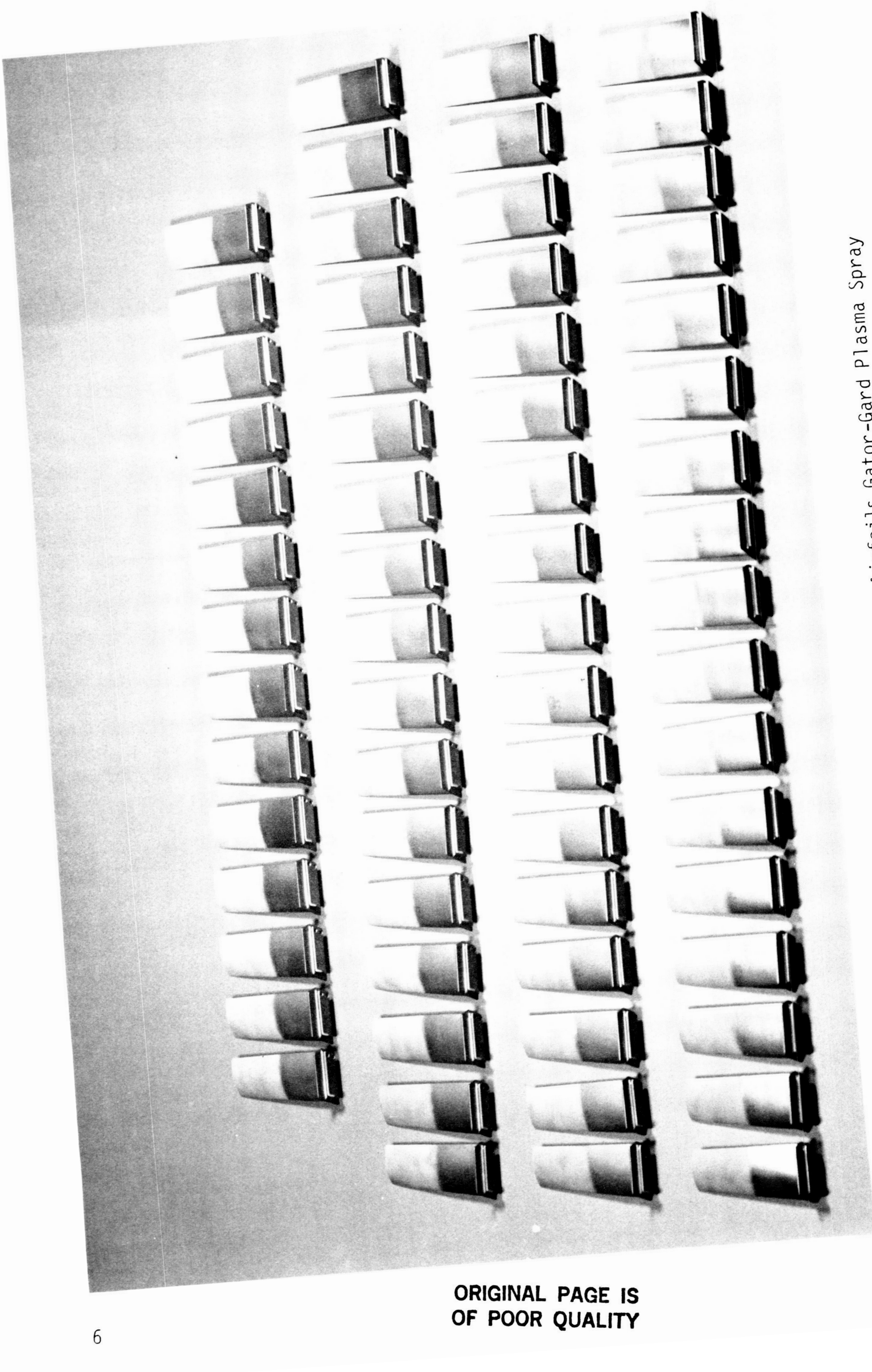

Figure 2 JT9D AMS 4928 7th Stage Compressor Airfoils Gator-Gard Plasma Spray
Coated with 88WC-12Co

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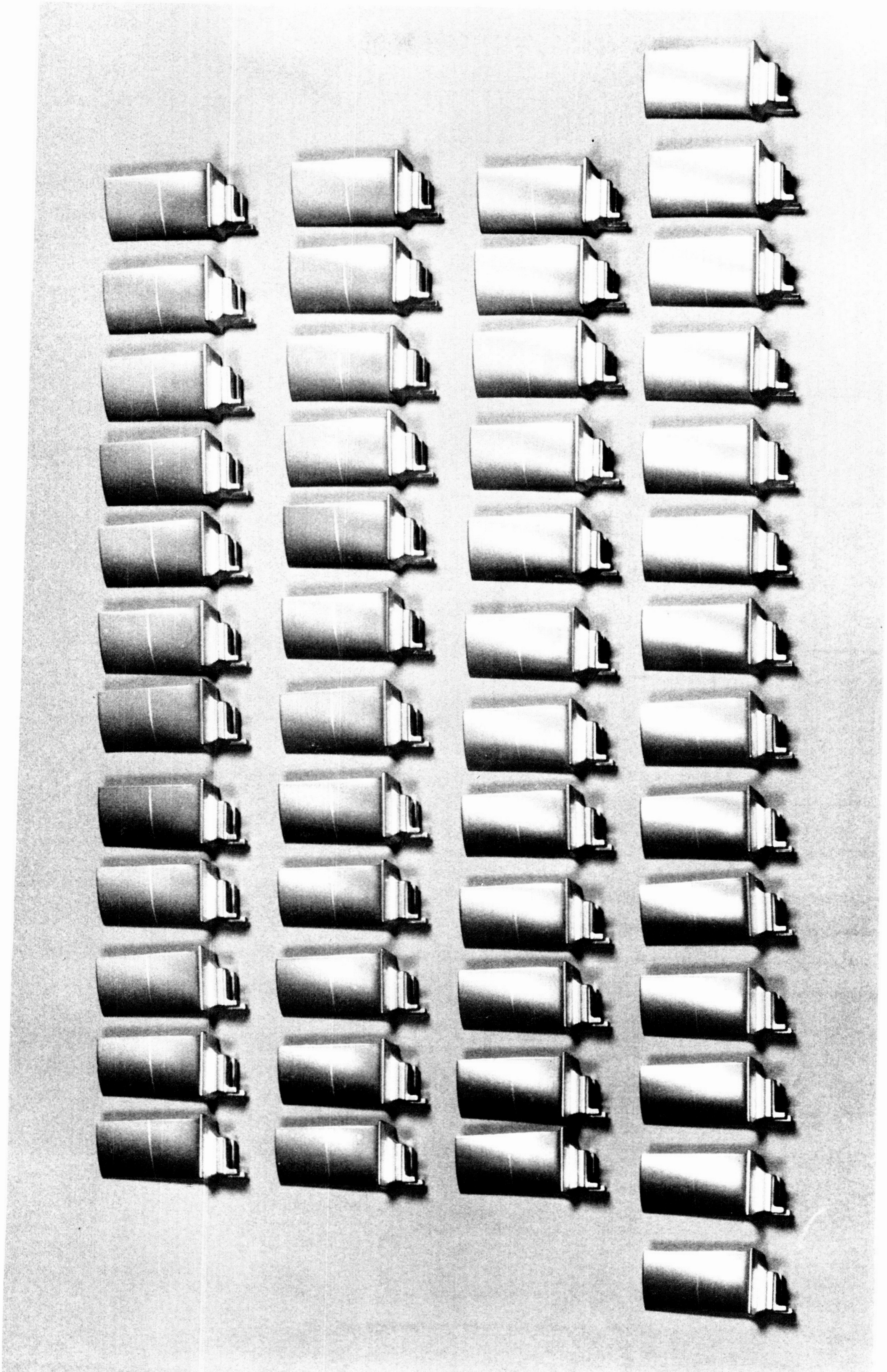

Figure 3 JT8D AMS 5616 12th Stage Compressor Airfoils 60 KW Plasma Spray Coated with 88WC-12Co and Overcoated with SermeTel 5380

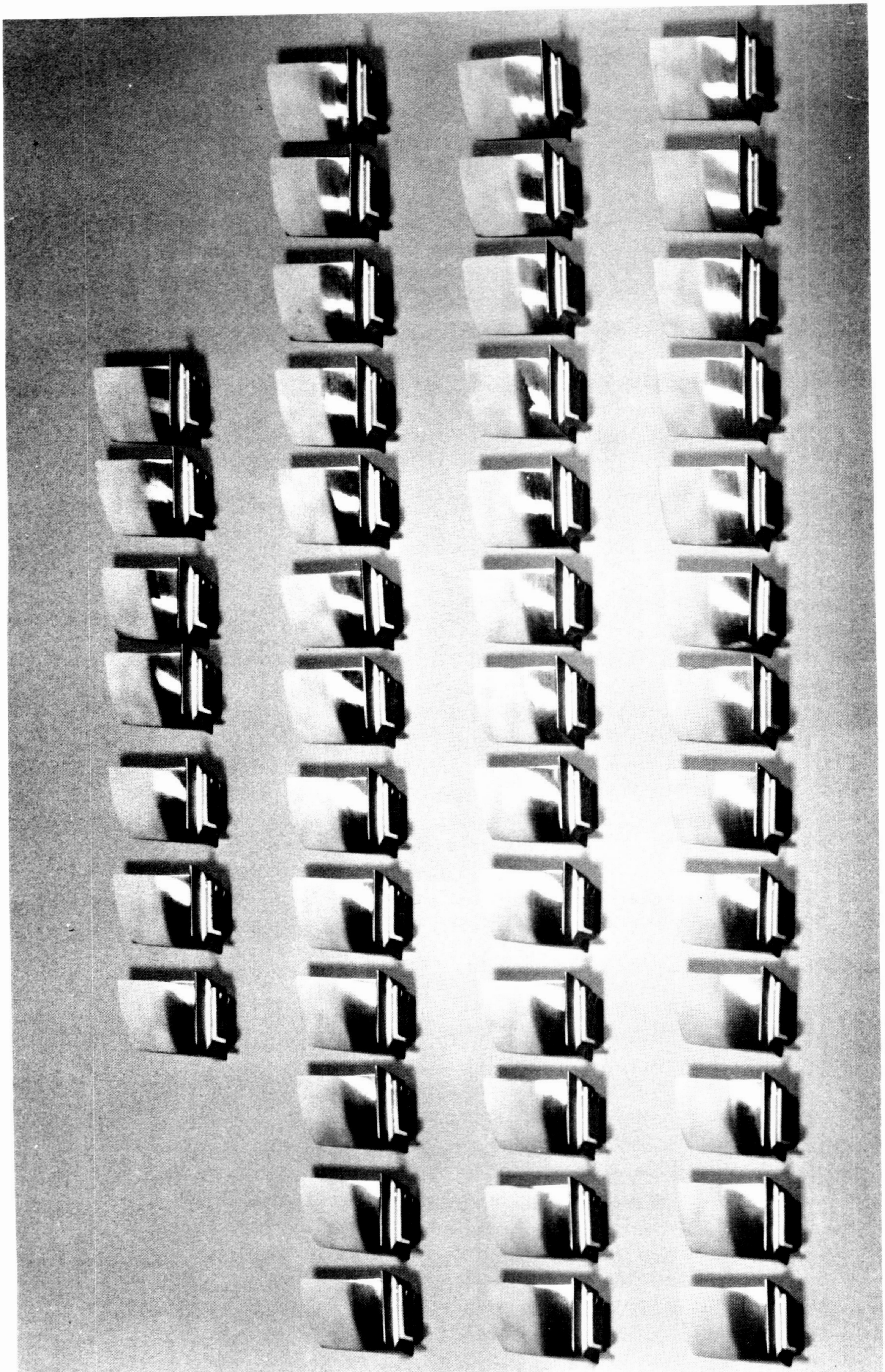

Figure 4 JT9D Incoloy 901 14th Stage Compressor Airfoils Gator-Gard Plasma Coated with 88WC-12Co

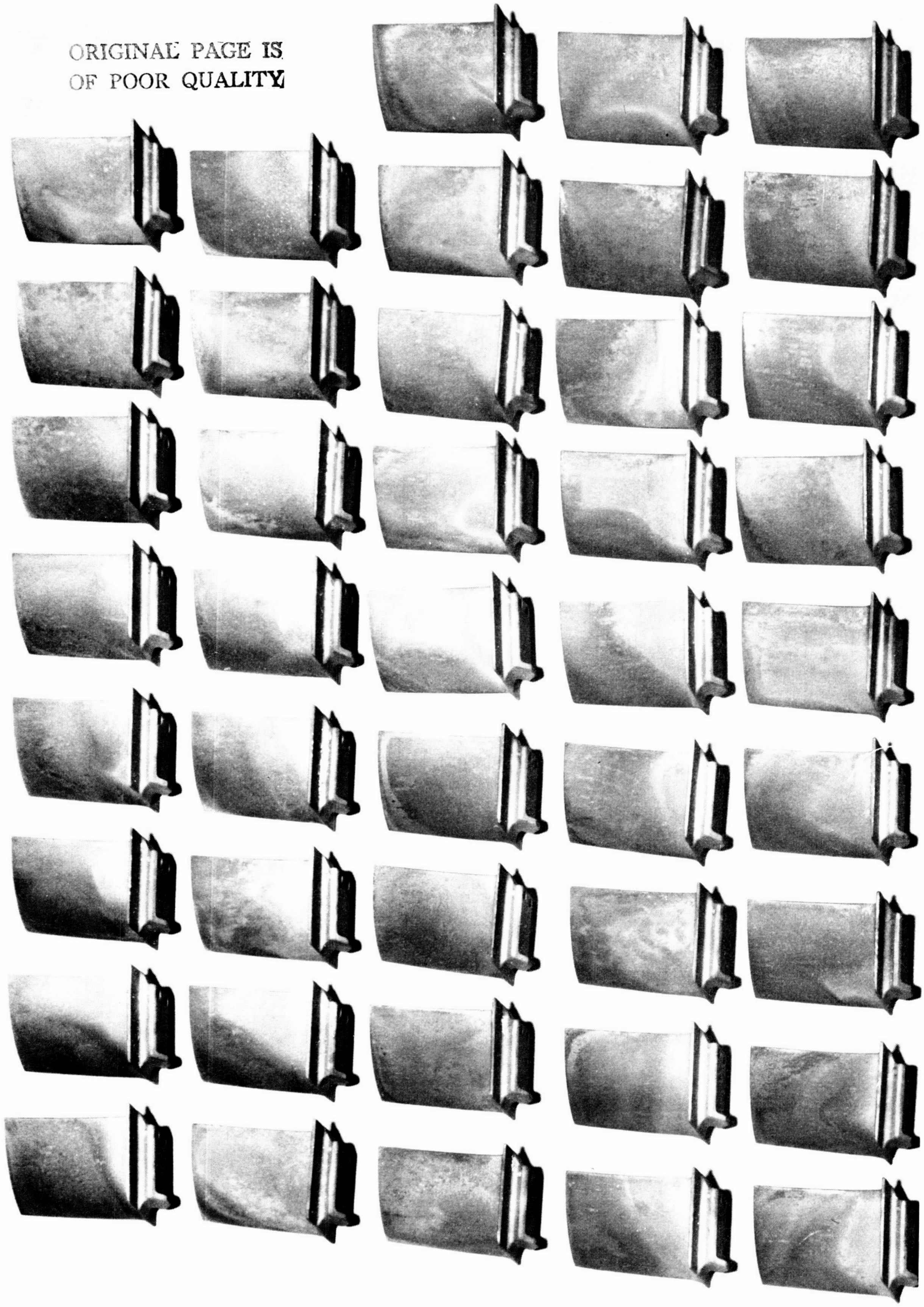

Figure 5 JT9D Incoloy 901 14th Stage Compressor Airfoils Pack Diffusion Coated With Cr+B

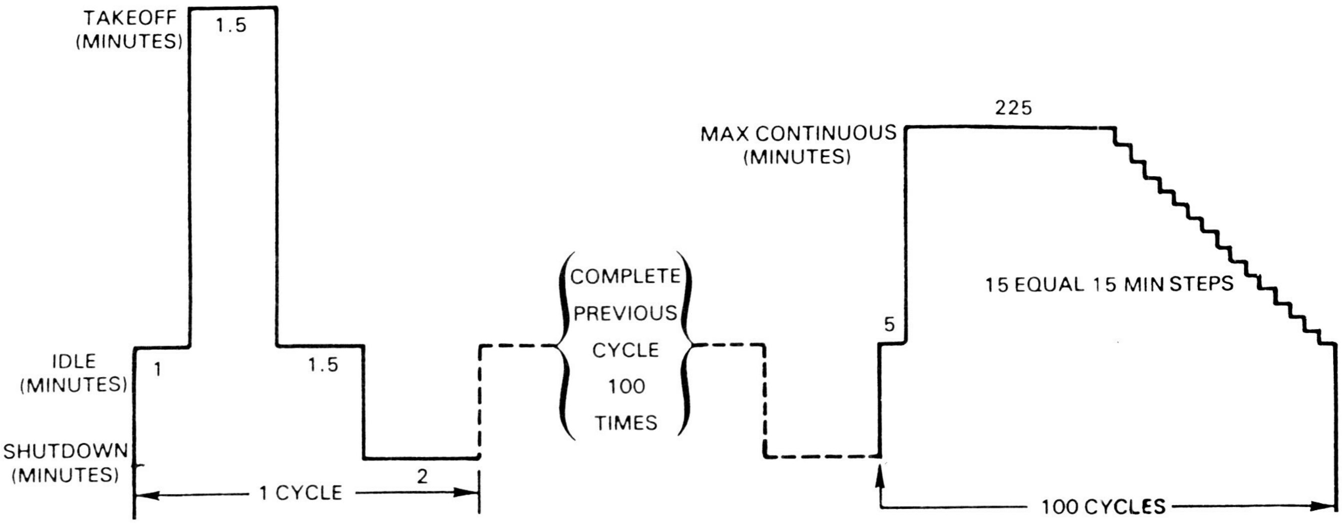

Figure 6 Schematic of JT8D Experimental Test Engine Cycle Showing 100 Cycles of 1000 Cycle Endurance Test

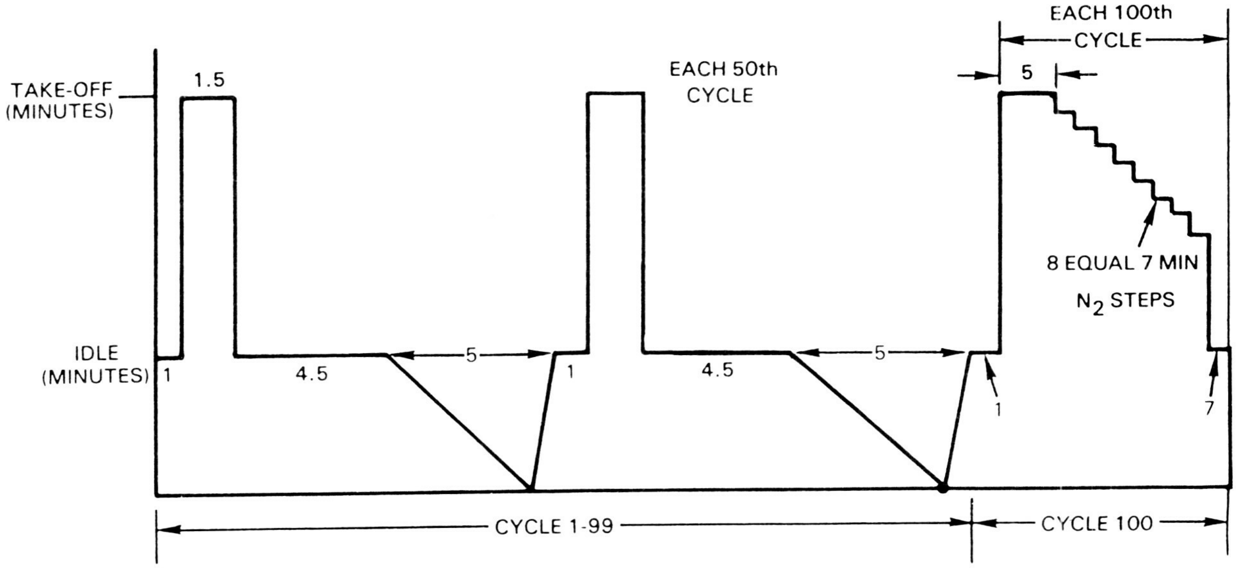

Figure 7 Schematic of JT9D Experimental Test Engine Cycle Showing 100 Cycles of 1000 Cycle Endurance Test

4.0 ENGINE TEST ANALYSIS

JT8D and JT9D engine tests were terminated prior to completion of the planned number of test cycles due to premature fractures of engine components.

JT8D Engine Test

One Gator-Gard plasma spray coated 88WC-12Co eighth stage AMS 4928 compressor blade fractured transversely through the airfoil approximately 1 1/2" above the root platform (Figure 8). Binocular and scanning electron microscope examinations revealed fatigue which progressed from a Gator-Gard coated airfoil surface approximately 0.01 - 0.03" from the trailing edge (Figure 9). Metallographic examination of a longitudinal section through the airfoil at the fatigue origin revealed a transgranular fracture path.

Post test inspection of the twelfth stage AMS 5616 airfoils, plasma spray coated with 83WC-17Co, using the 60 KW process, indicated no evidence of cracks. All of these airfoils were still acceptable for engine operation.

JT9D Engine Test

One Gator-Gard plasma spray coated 88WC-12Co seventh stage AMS 4928 compressor blade fractured through the airfoil approximately 2 5/8" above the root platform (Figure 10).

Binocular and scanning electron fractographic examination of the JT9D seventh stage airfoil fracture surface revealed high cycle fatigue (HCF) which had progressed for approximately 7/8" from an origin at the trailing edge surface, and for approximately 5/32" from an origin in vicinity of the leading edge (Figures 11 and 12); rubbed leading edge fracture surface precluded identification of the exact origin location. Fracture terminated in tensile overload between the extremities of the two HCF progressions.

Metallographic examination of plasma coated sections through the leading and trailing edges revealed transgranular HCF fracture paths; there were no apparent material or processing defects at the fatigue origins (Figure 13). Examination of a transverse section through the airfoil, inboard of the fracture, revealed that the coating conformed to the thickness requirement of 25 to 63 microns (1 to 2.5 mils). Coating microstructure was similar to the coating tested in Task VI.

Incoloy 901 fourteenth stage airfoils coated with either Gator-Gard plasma spray 88WC-12Co on pack diffusion applied Cr+B did not exhibit any detrimental conditions which would have precluded additional engine testing.

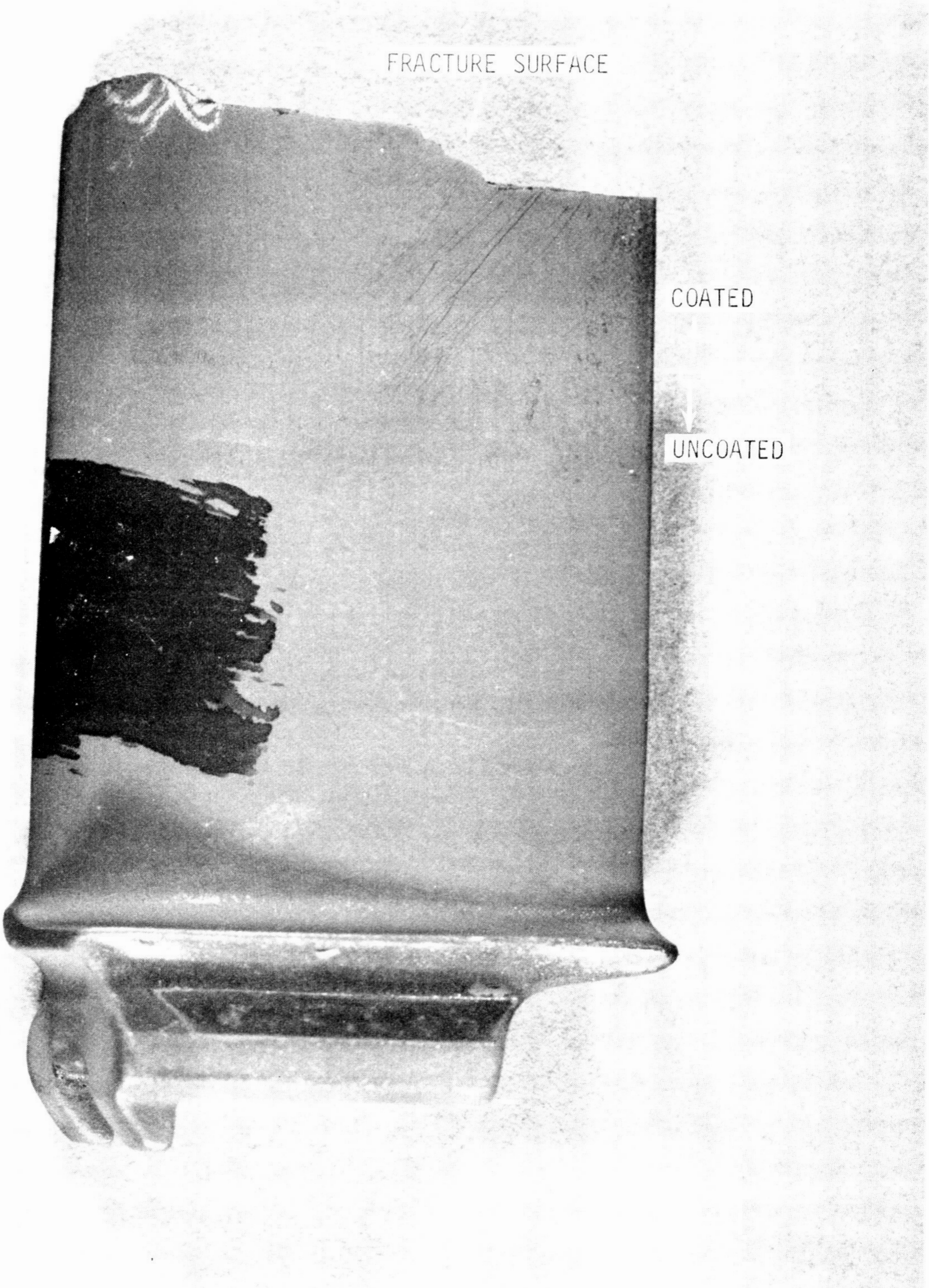

Figure 8 JT8D Engine Operated 8th Stage AMS 4928 Compressr Blade Showing Fracture in Gator-Gard Plasma Sprayed 88WC-12Co Coated Airfoil Region

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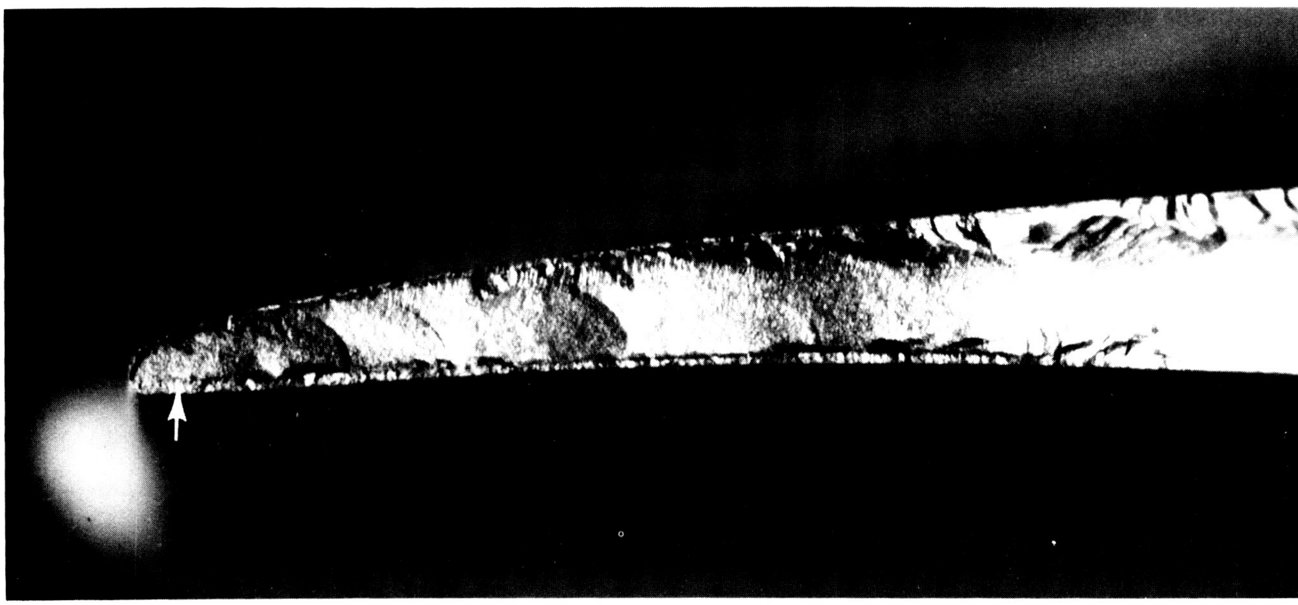

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Figure 9 JT8D 8th Stage Engine Operated AMS 4928 Compressor Blade Gator-Gard Plasma Sprayed with 88WC-12Co Showing Transverse Fatigue Fracture Through Coated Area From Origin Near Trailing Edge (Arrow)

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Figure 10 JT9D 7th Stage Engine Operated AMS 4928 Compressor Blade Showing Fracture (Bracket A) in Gator-Gard Plasma Sprayed 88WC-12Co Coated Airfoil Region (Bracket B)

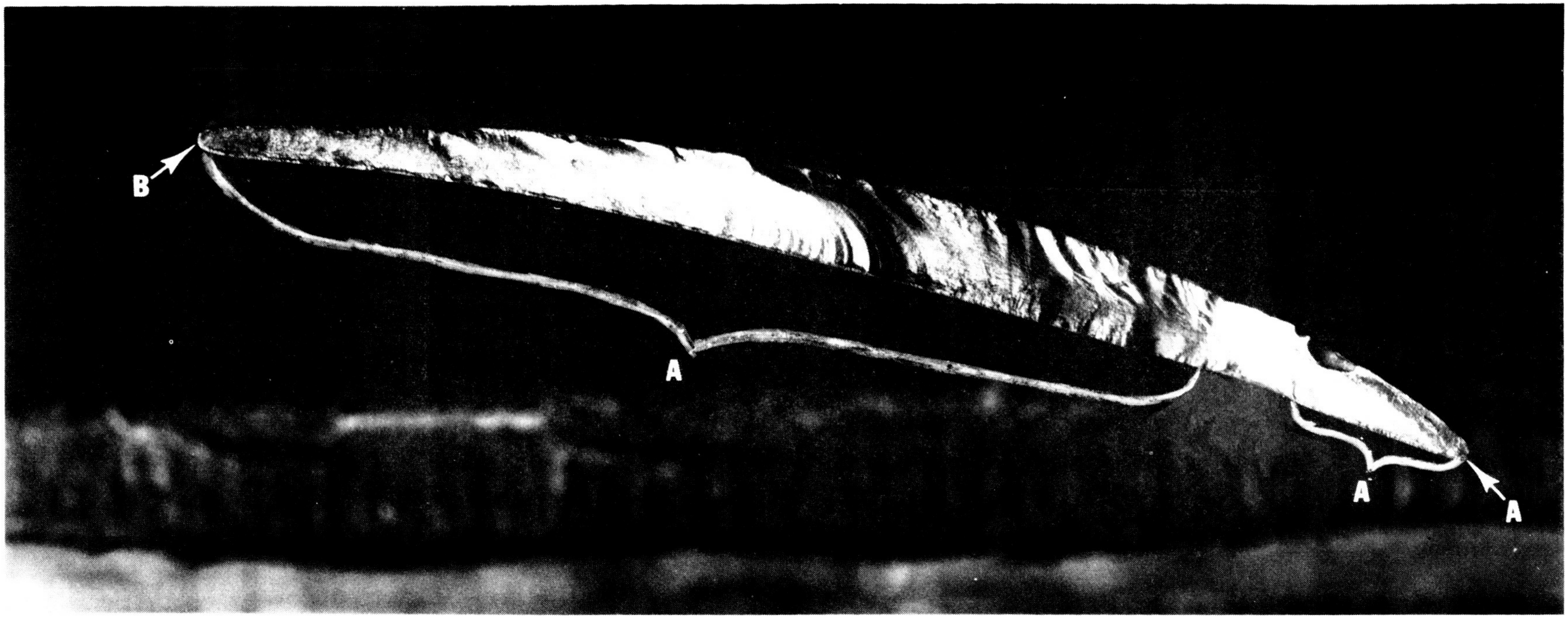

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Figure 11 Fracture Surface of JT9D 7th Stage AMS 4928 Engine Operated Compressor Blade Gator-Gard Plasma Spray Coated With 88WC-12Co Showing High Cycle Fatigue (Brackets A) Originating at Leading Edge (Arrow A) and Trailing Edge (Arrow B)

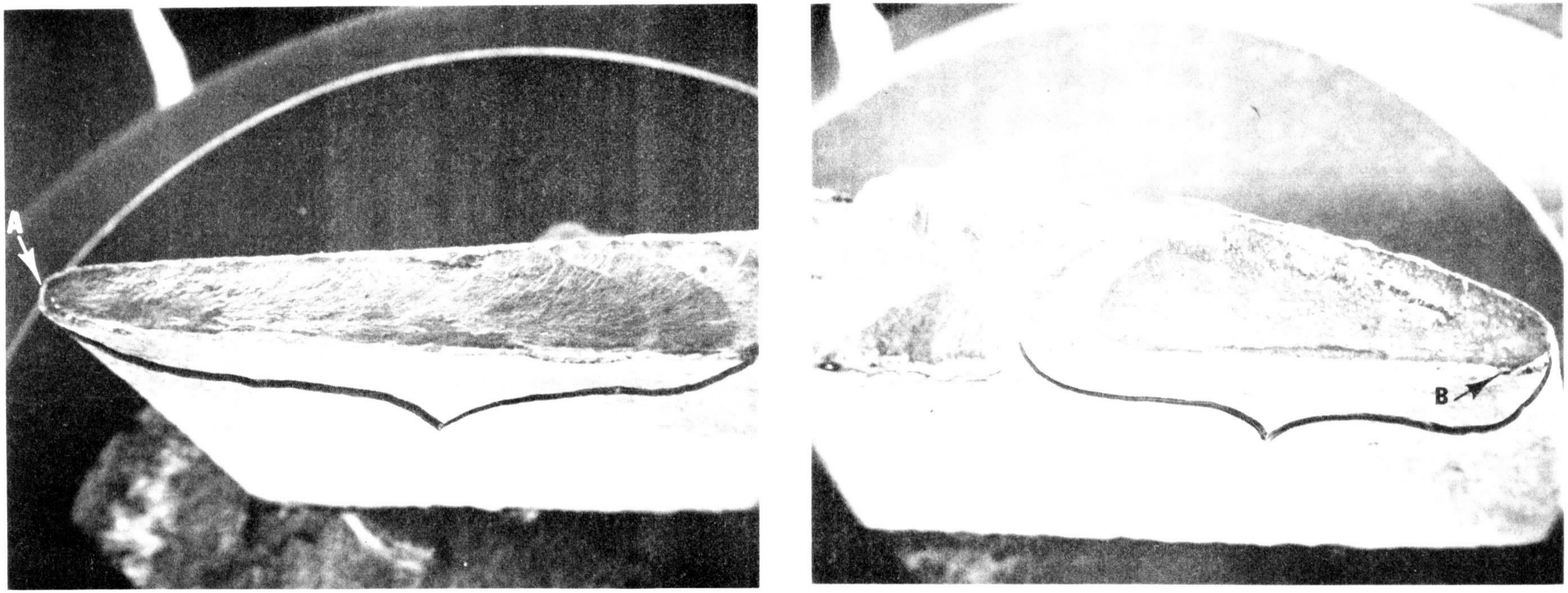

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Figure 12 Scanning Electon Fractographs of JT9D AMS 4928 Engine Operated Airfoil Trailing Edge (left) and Leading Edge (right) Fracture Surfaces, Showing High Cycle Fatigue (Brackets) From Origins at Trailing Edge (Arrow A) and in Vicinity of Leading Edge (Arrow B).

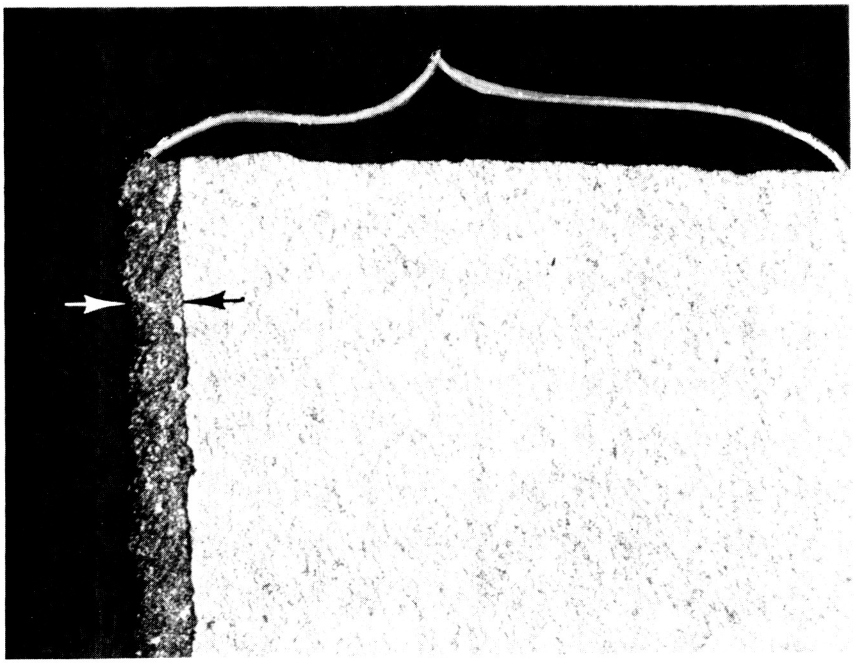

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Figure 13 Planar Section Through Trailing Edge of JT9D Engine Operated Fractured Blade Showing a Transgranular, High Cycle Fatigue Fracture Path (Bracket) and Gator-Gard Plasma Sprayed 88WC-12Co Coating (Between Arrows). A Similar Fracture Path Was Evident at Leading Edge.

5.0 DISCUSSION

The JT8D engine test was terminated after 744 cycles of a planned 1000 cycle test. In addition to coated compressor airfoils, an experimental weld repaired eighth stage stator anti-rotation lug was also incorporated for evaluation in this engine. This repaired anti-rotation lug experienced a fatigue fracture and was not found at engine disassembly. The part was presumed to have entered the gas path prior to the seventh stage and was the primary cause of heavy impact damage observed on the seventh stage blades. Examination of the impact damaged areas suggested that the event occurred some time prior to the termination of the test. Examination of the fractured JT8D compressor blade indicated there was no evidence of impact damage in the vicinity of the fatigue origin. Although the Gator-Gard plasma spray coating resulted in a significant debit to the eighth stage airfoil, the debit, by itself, was not sufficient to have caused the blade to fracture. However, failure of the anti-rotation lug would have resulted in increased eighth stage rotor vibratory stress which could initiate fatigue damage in the airfoils. Inspection of the remainder of airfoils in the rotor revealed various degrees of foreign object damage which precluded coating crack assessement on the other airfoils.

The JT9D engine test was terminated after 189 cycles due to a high cycle fatigue fracture of one Gator-Gard plasma spray coated seventh stage compressor blade. Fluorescent penetrant inspection of all remaining seventh stage coated airfoils revealed no crack indications, i.e. there was no incipient cracking on any other seventh stage airfoils. While the examination failed to detect the precise cause of the airfoil fracture, the possibility remains that the coating application process may have created a critical defect which resulted in the subject airfoil fracture.

6.0 CONCLUSIONS

Experimental land based engine tests were conducted to evaluate the performance of erosion resistant coatings applied to steel, nickel and titanium alloy compressor airfoils.

- o JT8D and JT9D engine tests were prematurely terminated due to high cycle fatigue fractures of the Gator-Gard plasma spray 88WC-12Co coating on AMS 4928 titanium alloy compressor blades.

- o AMS 5616 steel alloy airfoils coated with 83WC-17Co using the 60 KW plasma spray process and Incoloy 901 nickel alloy airfoils coated with either Gator-Gard plasma sprayed 88WC-12Co or pack diffusion applied Cr+B did not fracture or experience fatigue damage.

- o Airfoil fracture of the JT8D airfoil is believed to have occurred as a result of the fracture of another engine component which resulted in increased eighth stage vibratory stress. Fracture of the JT9D seventh stage airfoil was the result of fatigue originating in the Gator-Gard plasma spray 88WC-12Co coated section of the AMS 4928 airfoil at the leading and trailing edges.

- o Erosion resistant coatings are available which will provide increased protection from particulate erosion. However, on titanium alloy airfoils, the use of such coatings can significantly reduce airfoil fatigue strength. Improved coatings and coating processing methods will be required to minimize this fatigue strength loss if erosion resistant coatings are to be successfully used.